Real-Time Safety Monitoring & Prediction for the National Airspace System

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Motivation

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- With projected increases in national air traffic, advanced tools will be needed to maintain the current level of NAS safety, and aid in decision-making at all levels
  - Optimal decisions require knowledge of the current state of the NAS, and its future state
- Pilots, flight controllers, and other NAS operators need situational awareness to make informed decisions to avoid unsafe events
- Currently, NAS operators must
  - Consolidate operations-related information from disparate sources
  - Apply domain knowledge to interpret the current NAS state and forecast future NAS state
- Challenges include
  - Time- and workload-intensive
  - Information may be imprecise, inaccurate, incomplete, and inconsistent

Research Goals

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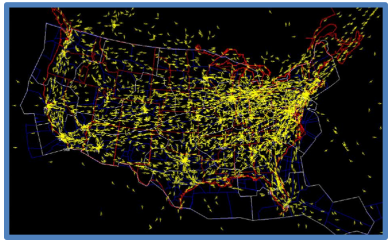

NAS

Real-time Safety Monitoring

Prediction of Unsafe Events and Future Safety

Pilots/ATC/...

Flight plans, flight tracks, weather, etc.

Estimate of current state of NAS safety; estimates of flight risks

Probability of future unsafe events; prediction of flight risks

Approach

- Safety Analysis & Modeling
  - What are the hazards to safe flight?
  - What unsafe events can occur?
  - Which hazards/events occur most frequently?
- Real-Time Safety Monitoring
  - How do we define “safety” and “risk” in the NAS?
  - How do we measure/quantify it?
  - How do we estimate the current state?
- Safety/Risk Prediction
  - Which unsafe events are likely to occur in the future, if no corrective action is taken?
  - What does the pilot need to be aware of?
  - What does a controller need to be aware of?

Definitions

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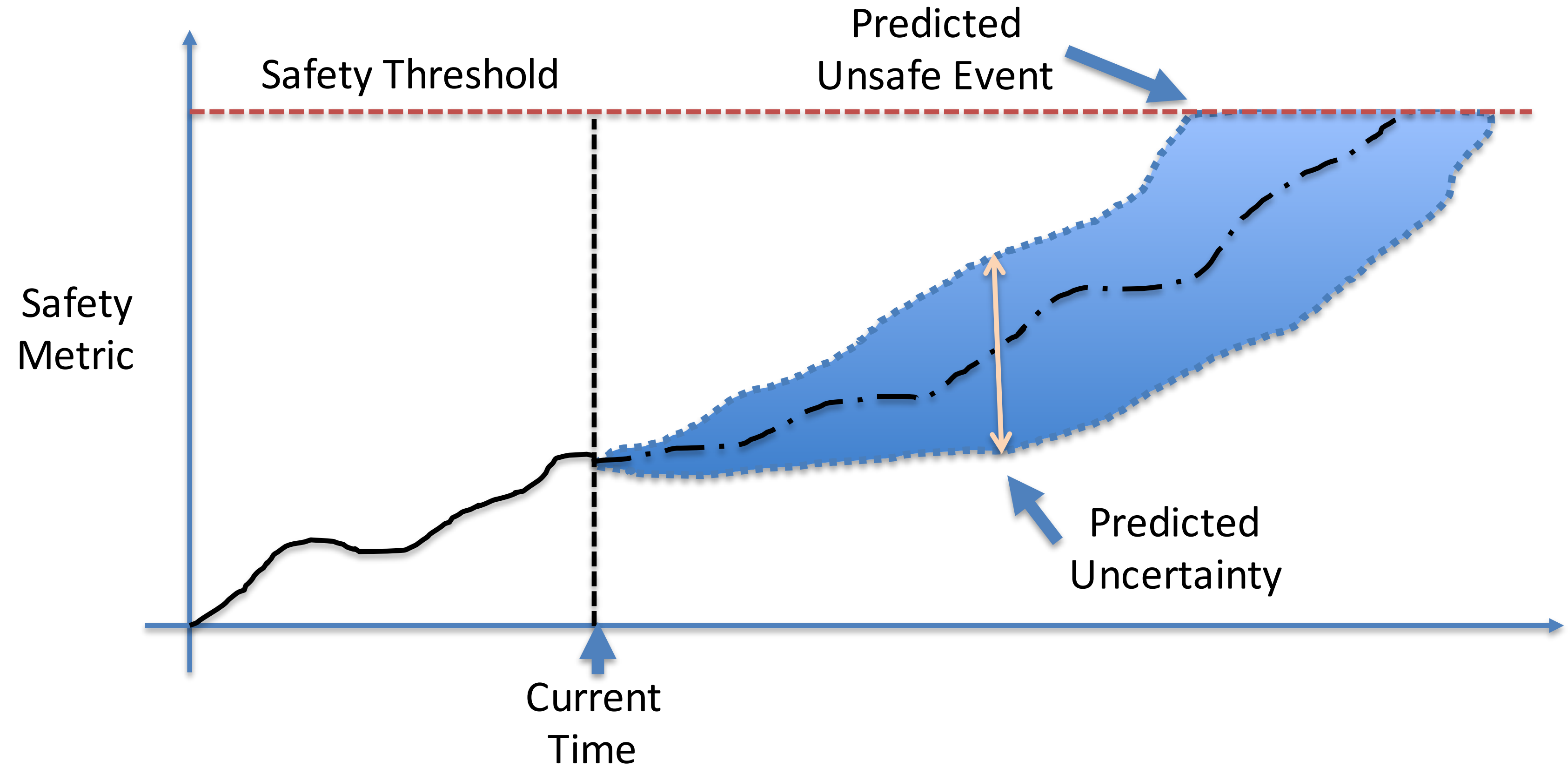
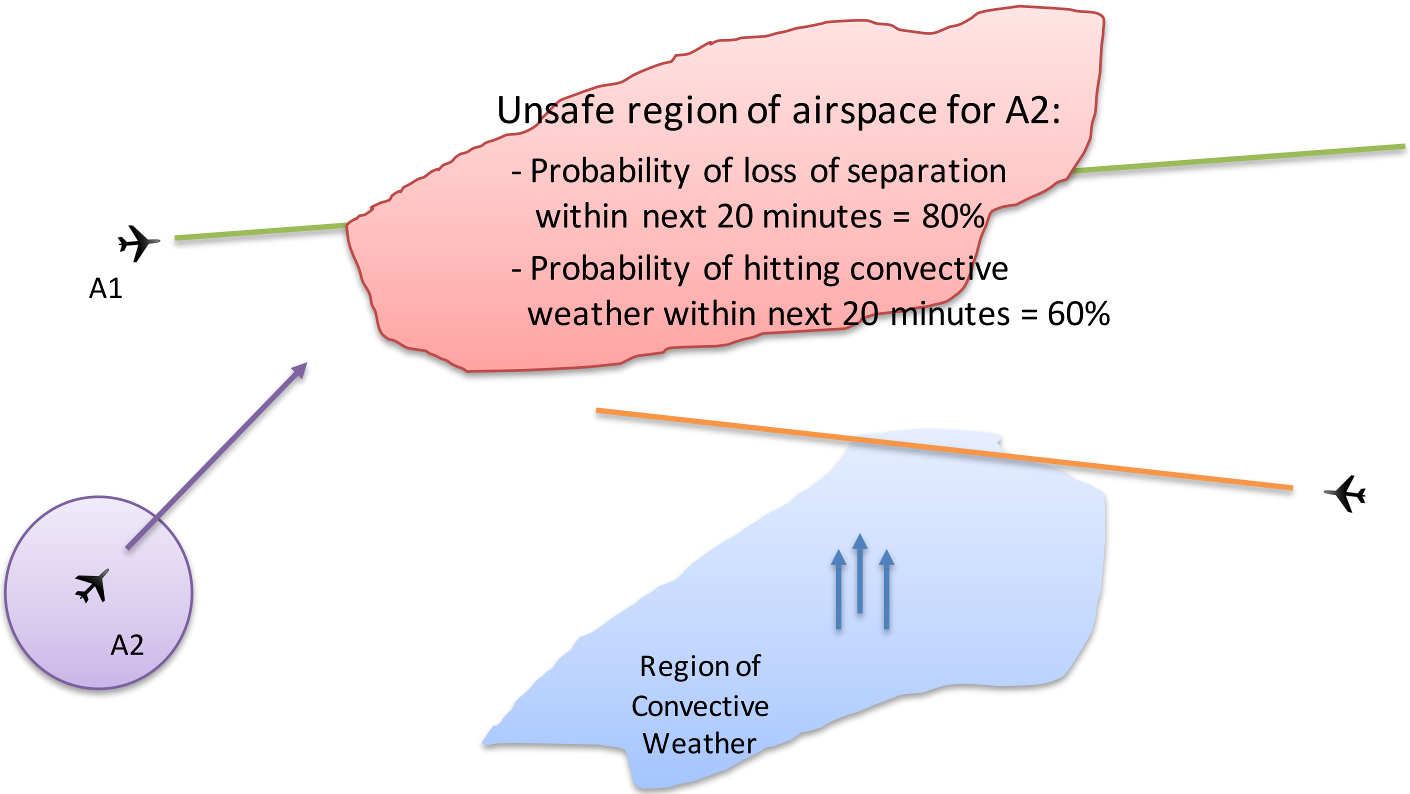
- Unsafe event
  - An event/situation that compromises NAS safety or established safety standards
  - Examples: loss of separation, loss of control, controlled flight into terrain, runway incursion, hard landing, tail strike, collision, etc.
- Hazard
  - A condition that contributes to unsafe events
  - Examples: convective weather, poor visibility, difficult terrain, etc.
- Safety metric
  - A quantitative measure of some aspect of safety of the NAS
  - Examples: distance between two aircraft, distance between aircraft and convective weather region
- Safety threshold
  - Some limit on a safety metric or set of safety metrics
  - Example: En-route separation of 5 nautical miles
- Safety margin
  - “Distance” between current safety metric(s) and safety threshold(s)

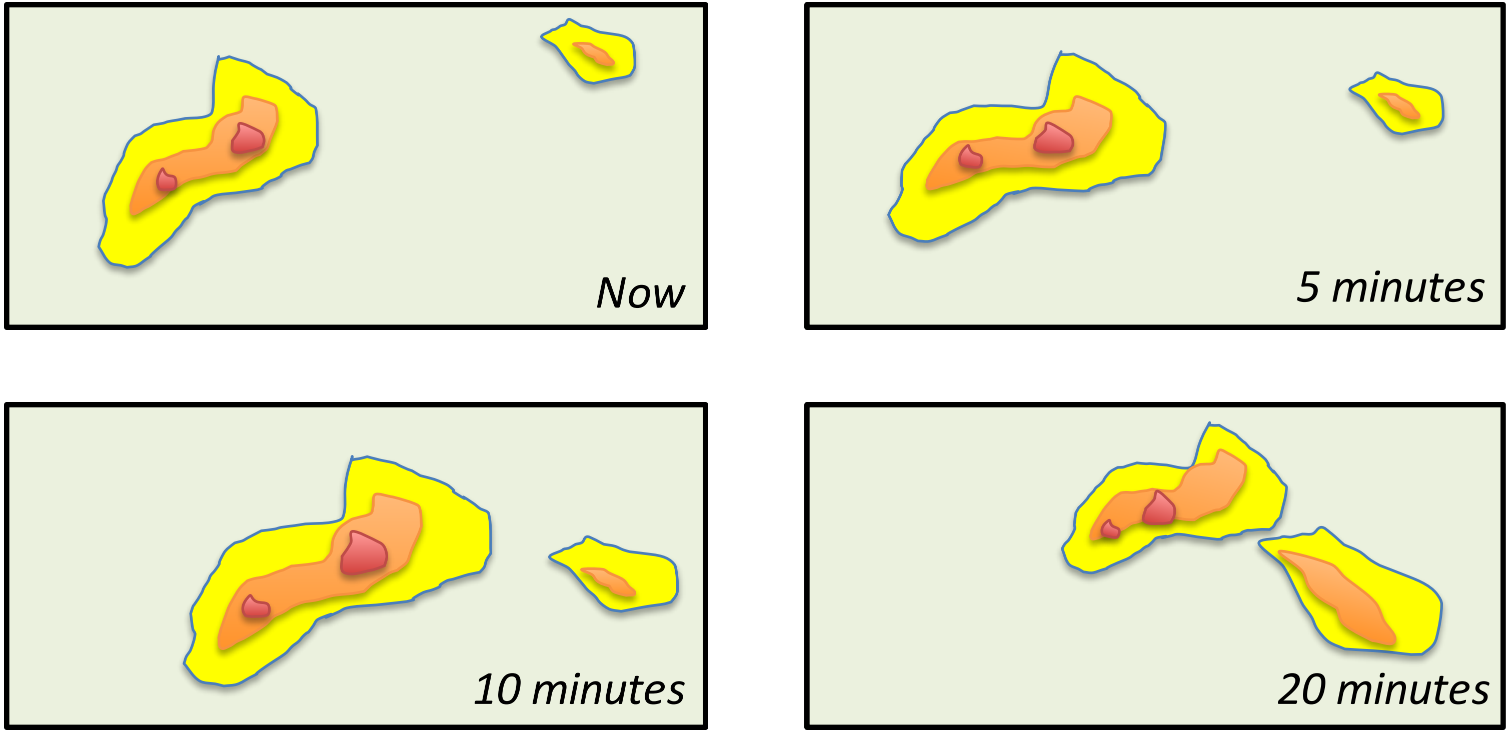
Concepts: 1-D Example



Concepts: Using Predictive Information



Concepts: Safety "Heat Map"



Safety Analysis: Hazards

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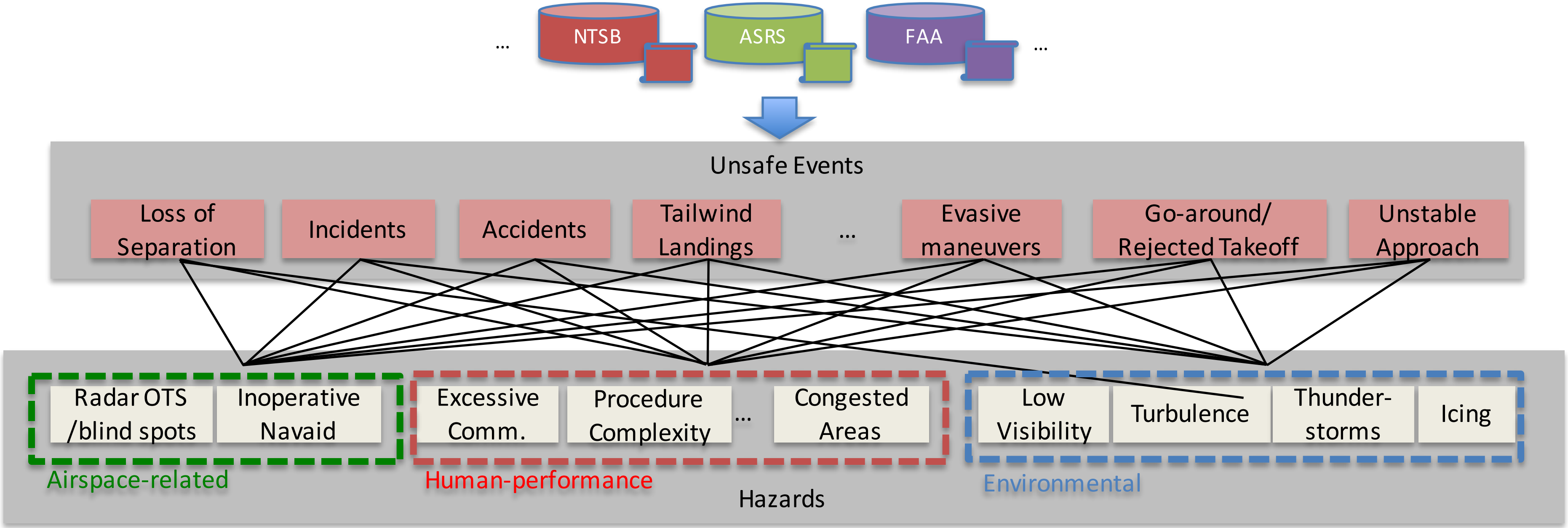
- Identify hazards that compromise safety analyzing reports from several national incident and accident databases
  - Down-select hazards based on potential to model, monitor, and predict



Safety Analysis

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- ASRS Reports
  - Topics
    - Altitude deviation
    - Bird or animal strike
    - Controlled Flight into Terrain
    - Communication
    - Fuel Management
    - Near Miss
    - Runway Incursion
    - Wake Turbulence
    - Weather
  - Wake turbulence, weather, and congestion are some common causes of unsafe events
- NTSB Accident and Incident Reports (2010 – 2015)
  - Turbulence, congestion, loss of situational awareness are some common causes of unsafe events

- <u>ASRS 1201963</u>: Unusually heavy CRJ-200 encounters wake turbulence shortly after takeoff at ATL. *"The new separation minimums between takeoffs in Atlanta needs to be altered. The company needs to present these issues to local ATC to prevent a major accident in the future."*
- <u>ASRS 1195051</u>: Deviating for weather puts flight in conflict with SUA
- <u>NTSB 4/27/12 incident</u>: Loss of Separation due to simultaneous independent runway operations on runways that do not physically intersect but whose flight paths intersect (LAS, go-around on 25L, departure on 19L; two controllers)
- <u>NTSB 12/1/11 incident</u>: Runway incursion caused by Tower Local Control clearing aircraft to cross runway immediately after clearing another aircraft to depart

Safety Analysis: Hazards

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Example hazards, based on category

Airspace-related Hazards

Hazard	Collision	Loss of control	CFIT	Injury Accident or Incident	Property Damage
Glideslope aids (e.g., VASI, PAPI, ILS glideslope) - inop		x			
Radar coverage - OTS or blind spots	x		x		
Communication - facility OTS or blind spots	x		x		
Communication - handoff automation OTS	x		x		
Lights - inop				x	x
Lights - misleading, nearby airport			x		
Lights - bright LED, runway or approach					x
Alternatives - few available (e.g., nearby emergency landing sites)				x	x

Environmental Hazards

Hazard	Collision	Loss of control	CFIT	Injury Accident or Incident	Property Damage
Weather - significantly worse than forecast	x	x	x	x	x
Convective weather		x	x	x	
Hail					x
Rain - moderate				x	x
Icing		x			
Turbulence - moderate to severe		x		x	x
Wind - strong		x		x	x
Visibility	x	x	x		
Temperature		x	x		
Volcanic ash	x		x		x
Night	x	x	x	x	x
Low sun angle	x	x	x	x	x
Animal activity - birds				x	x
Animal activity - other				x	x
FOD				x	x

Human-performance Hazards

Hazard	Collision	Loss of control	CFIT	Injury Accident or Incident	Property Damage
Elongated flight path – due to re-route				x	x
Elongated flight path - due to excessive vectoring or maneuvering (e.g., for weather)	x	x	x		
Takeoff - significantly delayed				x	x
Multiple speed changes on approach	x	x			x
Required tasks (procedures) - number and complexity	x		x		
Incorrect operations/procedures	x	x	x	x	x
Emergency / non-nominal situations	x			x	x
Aborted / botched approach	x	x	x	x	x
Communication issues (e.g., difficult accents, inexperienced pilots, multiple frequencies for one controller, etc.)	x		x		x
Flow control restrictions - active (e.g., MIT)					x
Lack of attention - complacency, multi-tasking	x	x	x	x	x

Safety Modeling: Safety Metrics and Thresholds

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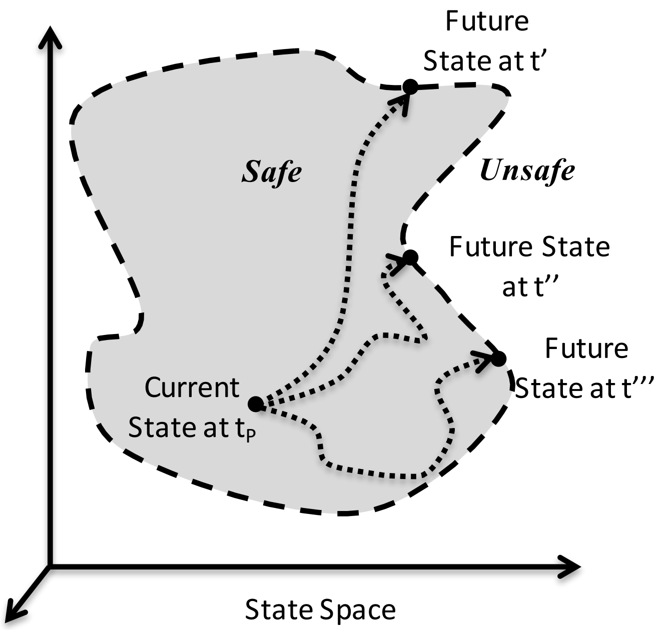
- Develop set of safety metrics to assess these hazards quantitatively
- Determine thresholds to define regions of reduced safety
  - Thresholds determined through analysis and consultation with subject matter experts
  - Data mining of archived operations data can also be utilized

Some Example Safety Metrics and Thresholds

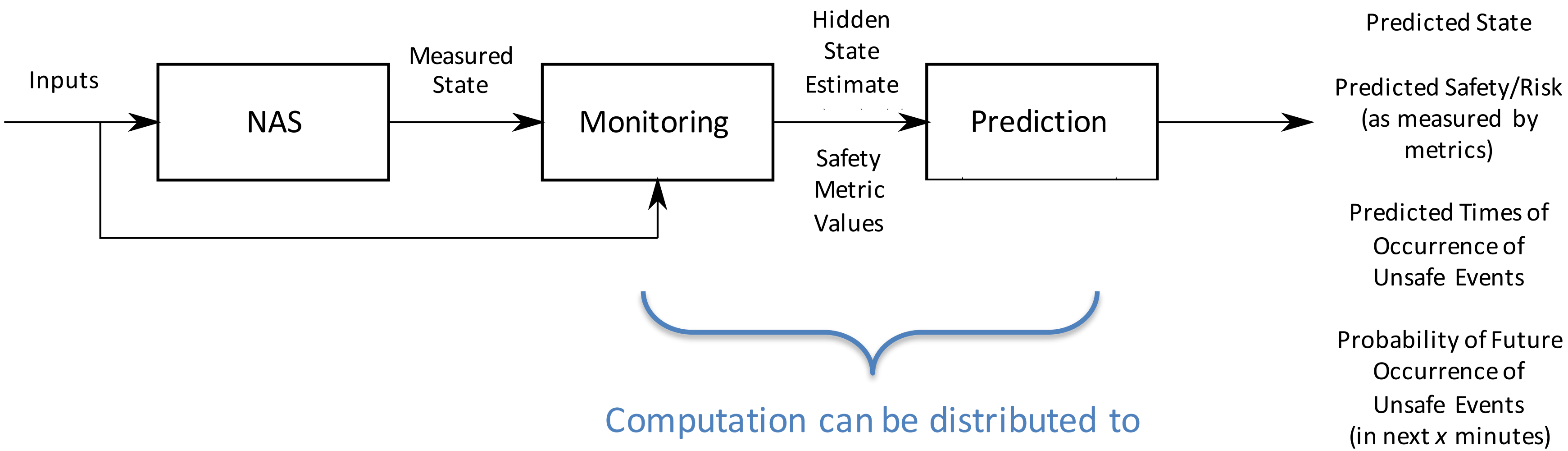
Safety metrics	Safety Metrics Function Arguments	Safety Metrics Function Outputs	Example of Threshold Functions
distance and heading to weather event	point of interest, weather severity, weather type, time	distance and heading	distance.thunderstorm $>$ 20 mi
weather at coordinate	point of interest, time	matrix of all weather categories (e.g., hail, rain, snow, mist, mixed, turbulence, thunderstorm, wind, microburst, windshear, etc.) and their relevant properties (e.g., severity, phase, type, persistence, direction of movement, etc., temperature, humidity)	A threshold is needed for each element of the matrix. Some examples: turbulence.intensity $<$ MODERATE, thunderstorm.intensity $\leq$ MODERATE, rain.intensity $<$ SEVERE
risk of wake turbulence	point of interest, time, {weather at coordinate}, type of preceding aircraft	risk category, e.g., low, medium, high	wake_turbulence_risk $\leq$ MEDIUM

Systems Modeling

- Models of NAS, e.g., aircraft, pilots, controllers, weather phenomenon, restricted airspace, etc.
  - Input to the framework (plug-and-play)
  - Model fidelity determined by application
- Uncertainty is inherent to the system
  - State of system, future inputs to the system, system dynamics (process noise), measurement error (sensor noise)
- Define functions that compute safety metrics from NAS state
- Determine thresholds that define the boundaries between safe from unsafe regions of the state space



Computational Architecture



Computation can be distributed to different regions of the NAS and consolidated for system-level safety assessment

Real-Time Monitoring

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- What is the current system state and its associated uncertainty?
  - Input: known system inputs and measured state
  - Output: state estimate (probability distribution)
- Estimation algorithms typically have two steps
  - Prediction step: Using system models, compute the probability distribution for the state one step ahead, starting from state estimate from previous step
  - Correction step: Use Bayes theorem to update prediction based on observations of the system state
- Given an estimate of the system state, an estimate of the safety, in the form of safety metrics, can be computed, along with safety margin and risk assessment

Prediction

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- Requires dynamic models of the system
- Algorithms use models to simulate the system ahead
  - Require some knowledge of future system inputs
    - Examples: flight plans, weather forecasts
    - This is highly uncertain; and this uncertainty must be included
  - Simulate forward in time to some specified prediction horizon (for example, 20 minutes)
    - Determine if and when predicted state violates safety thresholds
- Algorithms must handle uncertainty
  - Uncertainty is present in the current state estimate, in the future system inputs, in the system models, etc.
  - Example: Monte Carlo sampling – simulate forward many realizations (samples), sampling from all uncertain variables

Uncertainty Management

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Inputs (e.g., weather, Departure push-back, Airspace demand/capacity) → Model → Outputs (e.g., delay propagation, conflict prediction, safety/risk analysis)

Estimate uncertainty

Modeling uncertainty

Propagate all uncertainty through model

Uncertainty Characterization

- Challenges:
  - Existing work is mostly based on assuming Gaussian distributions
  - Accurately estimate probability distributions
- Ongoing work:
  - Systematically account for uncertainty

Uncertainty Propagation

- Challenges:
  - Existing uncertainty propagation methods are very simplistic with assumptions → not rigorous
- Ongoing work:
  - Rigorous methods → sampling, analytical
  - Advanced Monte Carlo-based
  - Analytical optimization-based

Uncertainty Management

- Address variety of issues:
  - Identify what input factors have significant impact on outputs
  - Correct/mitigate/control inputs to meet acceptable output margins
- Challenges:
  - Little to no existing work to manage existing uncertainty
- Ongoing work:
  - Global-Local sensitivity analysis
  - Optimization-based procedures

Consolidating Safety Metrics

Overall Likelihood of Being Unsafe

$$P(\cup_i E_i)$$

Likelihood of Being Unsafe
E_1: Aircraft Separation Violation

$$P(E_1) = P(\bigcup_{\forall i,j}^{i \neq j} A_{ij})$$

A_{ij}
Aircraft "*i*" versus Aircraft "*j*" unsafe (all *i*, *j*)

$$P(A_{ij})$$

Likelihood that aircraft "*i*" and aircraft "*j*" violate minimum separation

Likelihood of Being Unsafe
E_2: Aircraft-Weather Violation

$$P(E_2) = P(\bigcup_{\forall i,j} W_{ij})$$

W_{ij}
Aircraft "*i*" versus Weather "*j*" unsafe (all *i*, *j*)

$$P(W_{ij})$$

Likelihood that aircraft "*i*" and weather "*j*" violate minimum separation

Likelihood of Being Unsafe
E_3: Congestion in region of interest

$$P(E_3) = P(\bigcup_{\forall i} C_i)$$

C_i
Congestion in Region "*i*" (for all *i*)

$$P(C_i)$$

Likelihood that region "*i*" is congested

- It is important to account for probability-based information from multiple safety-related incidents
- Use principles of conditional probability and total probability to compute an integrated probability metric

Example: Wake Turbulence in Terminal Airspace

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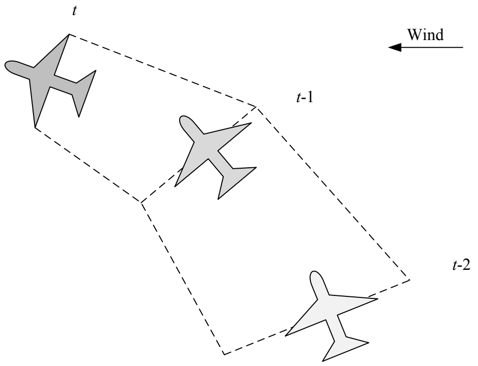
- Wake turbulence caused by wake vortex produced by aircraft generating lift at wing tips due to pressure differences
  - Weight, wingspan, speed of generating aircraft determine
    the initial strength and motion of the vortices
  - Ambient atmosphere (wind, stability, turbulence) determine the eventual motion and decay rate
- Induced rolling moment on an aircraft entering wake turbulence can cause it to lose control by exceeding roll control
- Pilots are responsible for maintaining adequate horizontal and vertical separation for wake turbulence avoidance during flight
- Controllers follow separation standards for arriving and departing flights in controlled airports



Example: Wake Turbulence in Terminal Airspace

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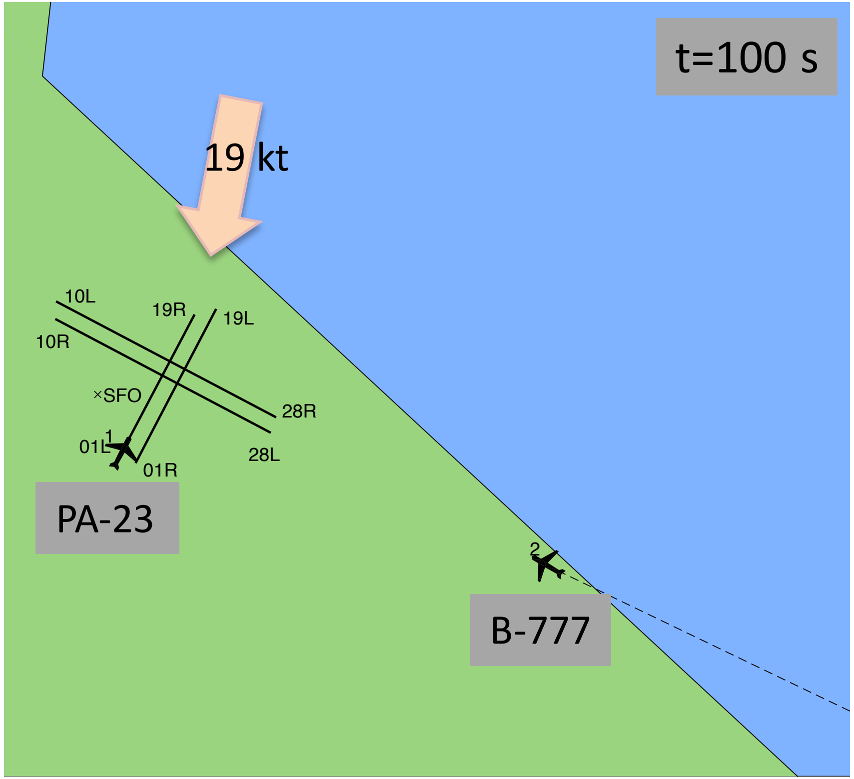
- Terminal airspace of San Francisco Airport (SFO)
- A1: Light Aircraft (e.g., Piper Aztec) waiting on runway 01L for takeoff clearance
- A2: Large Aircraft (e.g., Boeing 777) coming in for landing on crossing runway 28L
  - Lined up at 150 knots
- Safety metric: A1 will be in the wake of A2
- Strong crosswind (19 knots) coming from the north
  - A2 does a go-around as it is difficult to maintain directional control because of crosswind
  - Crosswind pushes wake turbulence of A2 down south toward A1



Example: Wake Turbulence in Terminal Airspace

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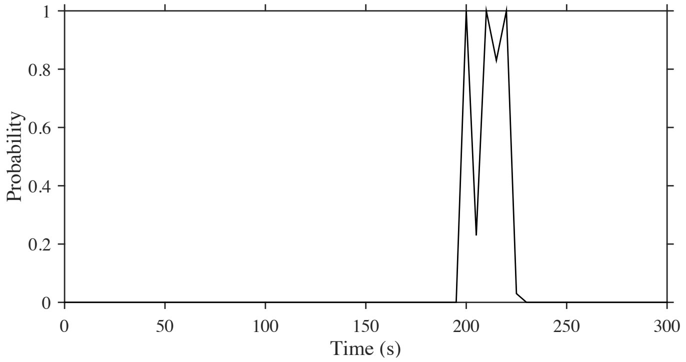
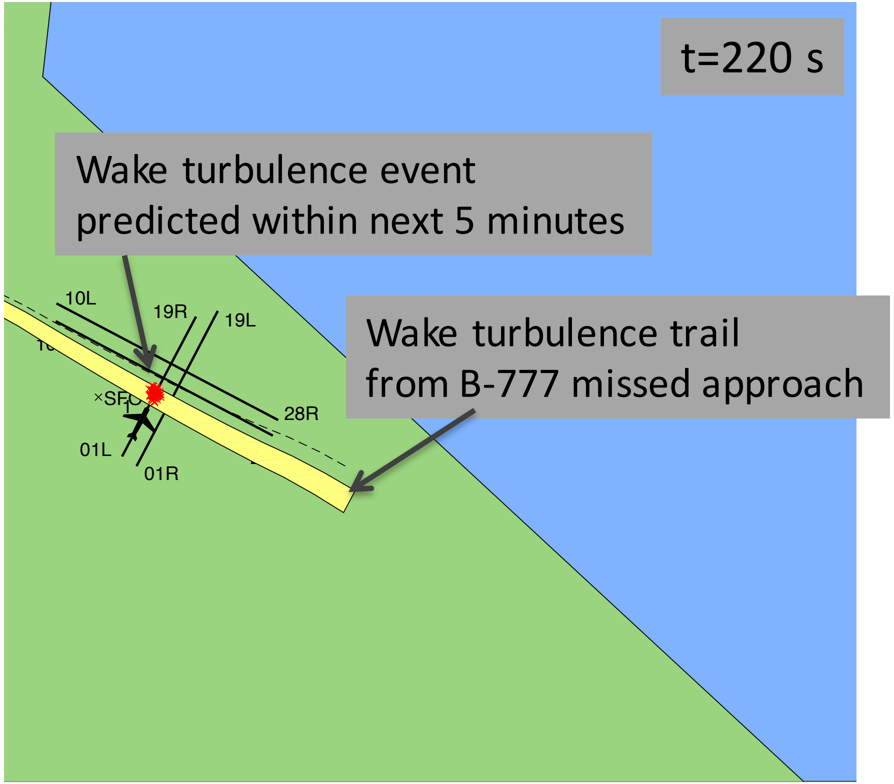
- From controller's perspective, probability of a wake turbulence event happening in the next 5 minutes can be computed
- This information can be used to show trouble spots on the controller's display
  - This could result in controller not giving takeoff clearance to A1 till the wake turbulence of A2 dissipates

Probability of A1 being in the wake of A2 within the next 5 minutes as a function of time





Summary and Future Work

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- Developing a methodology and framework for computing safety of the NAS in real-time
  - Define hazards, unsafe events, safety thresholds
  - Monitor and predict safety in real-time
  - Outputs can be used for improved situational awareness, decision support tools, improved decision-making
- Current work
  - Developing approach on SMART NAS Testbed
  - Our tool, currently in development, subscribes to airspace data, computes safety metrics, and makes predictions w/r/t airspace safety
- Future Work
  - Refine safety metrics, determine additional metrics
  - Refine algorithms through real data
  - More advanced monitoring and prediction algorithms
  - More advanced uncertainty quantification and propagation techniques